the time of formation, the early movement of the storm is most certainly determined by the action of the air masses surrounding it, and, a controlling air-flow from the direction of the Equator providing the first impulse may determine its entire future life history. Mitchell (1) has shown that tropical cyclones rarely, if ever, form in the eastern two-thirds of the Caribbean Sea. How is this fact to be interpreted? Is it because dominant air-flows from the direction of the Equator are effectively blocked by the South American continent?

REFERENCES TO LITERATURE

(1) Mitchell, Charles L. West Indian Hurricanes and other Tropical Cyclones of the North Atlantic Ocean. Mo. Wea. Rev. Supplement, No. 24, 1924.
(2) Tingley, Franklin G. The Genesis of a Tropical Cyclone. Mo. Wea. Rev., Vol. 59, September 1931.
(3) Hurd, Willis E. The North Atlantic Hurricane of October 13–29, 1926, H. O. Pilot Chart North Atlantic Ocean, October 1930.
(4) Hurd, Willis E. Tropical Cyclones of the Eastern North Pacific, H. O. Pilot Chart Central American Waters, June 1930.
(5) Cline, I. M. Tropical Cyclones. New York, 1926.

MONTHLY AND SEASONAL DISTRIBUTION OF SNOWFALL [1] IN CALIFORNIA

By MALCOLM SPRAGUE

[Weather Bureau, San Francisco, Calif., June 1934]

California, because of its great extent from north to south and its diversified physical features, is a region where the climatic elements have an exceptionally wide range. This is especially true of snowfall. On the extreme southern coast, snow has not fallen within the last 84 years, while the western slopes of the middle and northern Sierra Nevada include several localities where the annual mean snowfall approaches the record for the United States. The total fall is influenced more by altitude, proximity to the Pacific Ocean, shape and steepness of mountain slopes and their direction in relation to moisture-bearing winds, and by local topography, than by latitude. Topographical contrasts are especially noticeable in southern California, where semi-tropical fruits may be seen ripening near the bases of snow-covered mountain peaks. As an example of latitudinal influence, Imperial, near the southern border of the State, has an annual mean snowfall of 0.2 inch, while the coastal station of Crescent City (near), located some 620 miles farther north, has a mean of less than 2 inches. In contrast to this small south to north increase, modified by ocean influence, is the large increase within short distances west to east in the district adjacent to the line of the transcontinental railway which crosses the crest of the Sierra Nevada near Summit, Placer County. Within this area Colfax, elevation 2,421 feet, has an average annual snowfall of 25 inches; Blue Canyon, located 18 miles farther northeastward, elevation 4,695 feet, 203 inches; and Soda Springs, 19 miles east-northeast of Blue Canyon, elevation 6,752 feet, 410 inches.

The precipitation received in the form of snow, while consequential over only about half of the State, is a vital factor in all of the more important activities in California, providing a water reserve for navigation, mining operations, hydroelectric projects, and domestic and municipal consumption, and making possible many minor activities that depend on the others for their prosperity. The California snow-fields also have a recreational value and their use for winter sports has increased greatly during recent years.

SNOWFALL DISTRIBUTION BY MONTHS

Snow has fallen over the "High Sierra" in all months of the year, but over the valley floors and much of the coastal area, only occasionally during the winter and spring months. Daily amounts generally are inconsequential over the lowlands and drier portions of the State, and increase with increase in seasonal precipitation and in altitude up to 7,000 feet, reaching a maximum over the western slopes of the middle Sierra Nevada. The heaviest 24-hour snowfall of record in California was 60 inches at Giant Forest, Tulare County, on January 19, 1933, and the next heaviest was 59 inches at Summit on December 23, 1916.

The distribution by months for the State as a whole in percent of average seasonal amount is as follows: January, 26; February, 20; December, 18; March, 17; April, 8; November, 7; and October and May, 2 each. The total fall for the other 4 months is less than 1 percent of the seasonal average. This average distribution is fairly representative. However, in the warmer portions of northern and central California the midwinter months

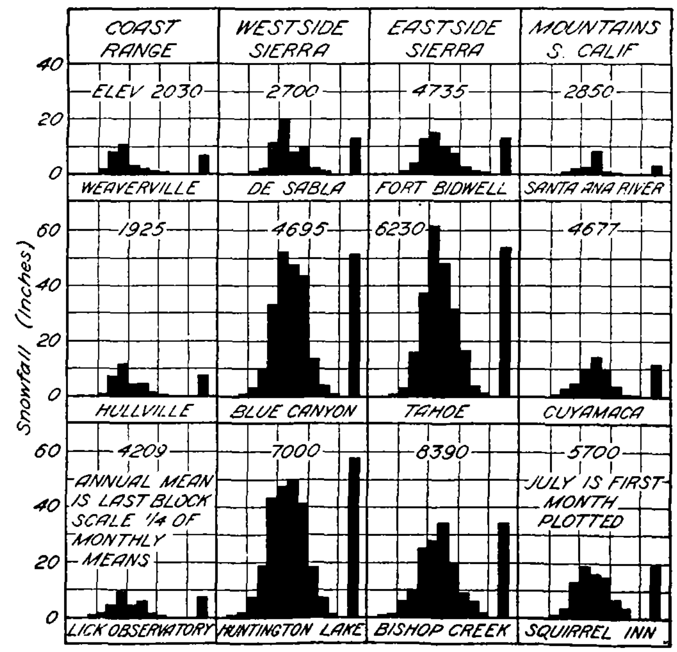

FIGURE 1.—Mean monthly snowfall distribution.

have a somewhat higher percentage than like months for the State as a whole. Similarly in the colder portions, especially over the eastern slopes of the southern Sierra Nevada, higher percentages occur in the spring months. The distribution over the southern slopes of the mountains of southern California is similar to that over the southern slopes of the southern Sierra Nevada. The monthly distribution for four groups of stations is illustrated in figure 1. Reading down from the left, the first group represents the Coast Range Mountains; the second the western, and the third the eastern, slopes of the Sierra Nevada; and the fourth, the mountains of southern California.

[1] Presented at the American Meteorological Society at Berkeley, Calif., June 21, 1934.

A longer period of record is needed to obtain representative monthly means for low-level than for high-level stations, as at the former several seasons may pass without snowfall, making it necessary in some instances to base a monthly mean on a single occurrence. Consequently monthly means for low-level stations are not comparable unless like periods of record are used, or the means adjusted. Monthly values show wide fluctuations at the moderate and high elevations also, but become more stable with increase in altitude.

The combined Summit-Norden-Soda Springs snowfall record is the longest in this State and will be used to show the range in monthly amounts for a district where conditions are relatively stable. In this area of heavy snowfall there have been years when snow did not fall from June to October, inclusive. The extremes for each month, in inches, are as follows:

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Least monthly	0	0	0	0	0	6	15	3	1	T	0	0
Greatest monthly	0	T	14	89	136	245	283	207	265	298	63	19

The April maximum entered above occurred in 1880, and was exceeded at Tamarack, where the greatest monthly amount was 390 inches in January 1911.

SEASONAL DISTRIBUTION

Average seasonal amounts range from a trace or less along the middle and southern coast and in a few southern low-level, interior localities, to 449 inches at Tamarack, Alpine County, elevation 8,000 feet. About one-third of the State has an elevation of less than 1,000 feet, and the average snowfall for this third is 0.5 inch, with seasonal totals ranging from zero to 1 inch over its southern and central portions and from 1 to 8 inches over its northern portion, the maximum amount occurring in the northern Sacramento Valley. The higher the level the greater the range in the seasonal averages up to an elevation of 8,000 feet; latitude, distance from the ocean, and total seasonal precipitation are the most important modifying factors. The average seasonal snowfall is shown in figure 2 and the average seasonal precipitation in figure 3.

These charts bring out the close similarity between the seasonal distribution of snowfall and precipitation over the Sierra Nevada and the Modoc Plateau, but elsewhere a dissimilarity, which increases as the percentage of total precipitation in the form of snow decreases. The isohyets closely follow contour lines, but are more regular, probably due to lack of sufficient reporting stations to bring out all irregularities of precipitation caused by orographic control. Lines of equal snowfall follow contour lines at the higher altitudes; also at the moderate levels, except in the warmer districts. The effect of direction of mountain slopes on snowfall is the same as on the total precipitation, the westerly and the southerly receiving a much heavier snowfall than the easterly and northerly, except over very limited areas influenced by local topography. Data are insufficient to evaluate the shadow effect to the leeward of high mountain ranges. Figure 4 represents the average seasonal precipitation and average seasonal snowfall in percentages of normal for the period from 1897–98 to 1932–33, inclusive.

This graph shows that the seasonal snowfall has a greater variability than the seasonal precipitation. During the period charted, the snowfall, expressed in percent of normal, ranged from 23 in 1930–31 to 215 in 1921–22, while the seasonal precipitation range was from 49 in 1923–24 to 153 in 1913–14. In general, the abnormalities of snowfall showed the same trend as those of precipitation, and in 26 of the last 37 seasons their departures from normal were in the same direction. Marked exceptions to this rule were in 1913–14 when the seasonal

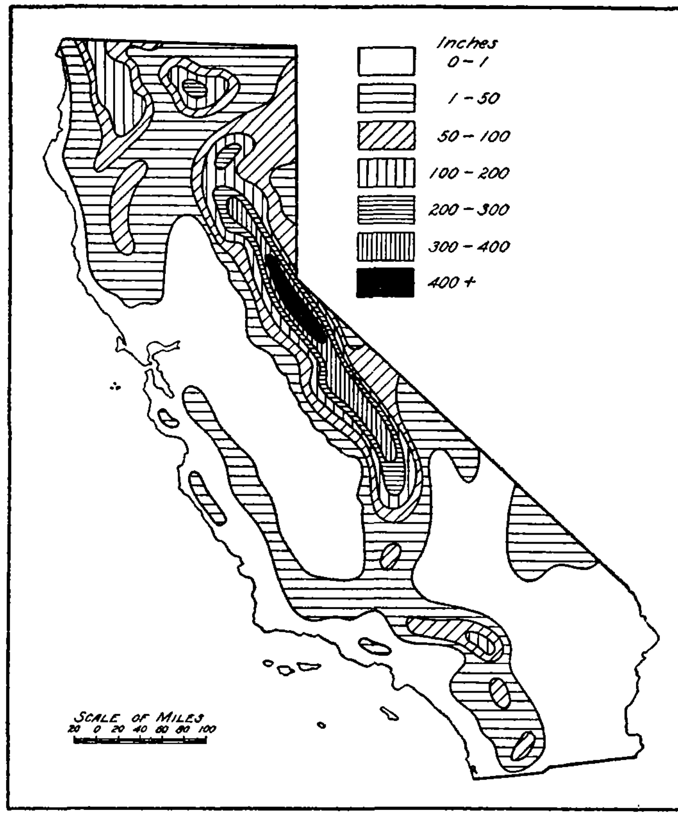

FIGURE 2.—California mean seasonal snowfall.

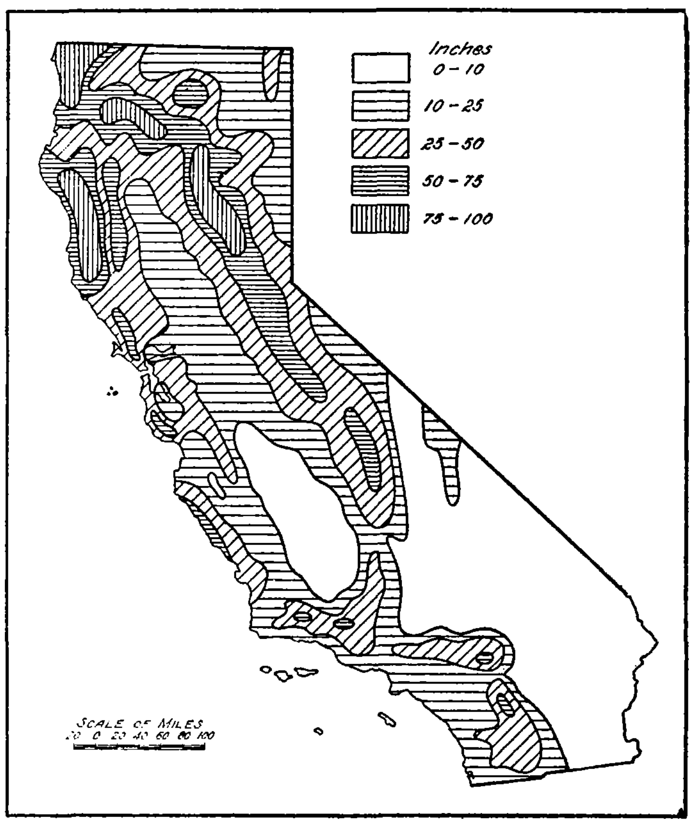

FIGURE 3.—California mean seasonal precipitation.

snowfall was 75 percent and the seasonal precipitation 153 percent of normal; and in 1932–33 when snowfall and precipitation percentages were 201 and 70, respectively. Seasonal totals varied greatly in areas of heavy as well as in areas of light and occasional snowfall, as will be emphasized by giving the seasonal extremes for

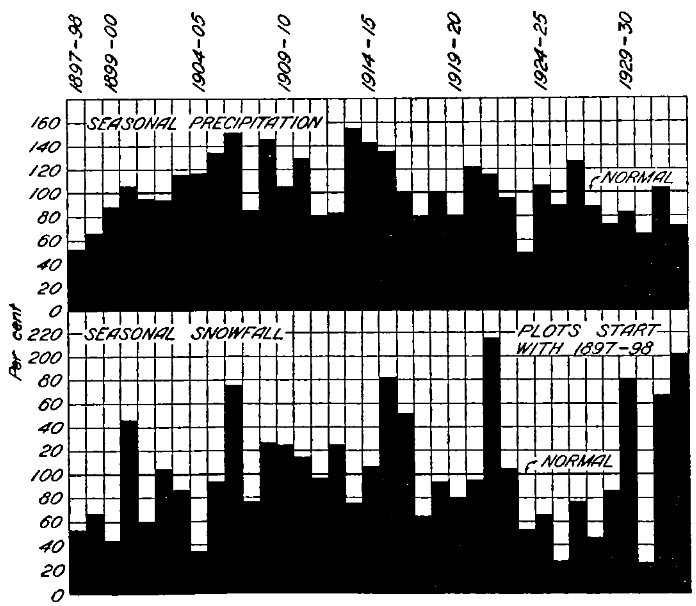

FIGURE 4.—Seasonal precipitation and seasonal snowfall.

Soda Springs and Tamarack. At Soda Springs they were 154 in 1880–81 and 783 inches in 1879–80; and at Tamarack, 266 in 1925–26 and 884 inches in 1906–07.

The snowfall was generally light during the first 9 seasons of record; mostly heavy during the next 11 seasons; light, with two exceptions, from 1917–18 to 1928–29, inclusive; and marked by wide fluctuations during the last 5 seasons, that of 1933–34 included. Figure 5 shows accumulated precipitation and snowfall departures, based upon means for the period of record. The year 1911 was used as the starting point of these graphs, which accentuate the effect of the tendency for like departures to predominate through a series of seasons and show a similarity in total precipitation and snowfall trends. There is a lag, however, in the snowfall changes in trend.

The average effect of altitude on seasonal snowfall was obtained by tabulating the seasonal totals for each 1,000-foot level, starting with stations having an average elevation of 500 feet. The number of records available decreased with increase in elevation, ranging from 239 for the 500 to 4 for the 7,500 and higher levels. The records used were fairly well distributed as to area, except for the 8,500- and 9,500-foot levels, where all were for stations located on the eastern slopes of the southern Sierra Nevada. This grouping probably accounts for the much smaller mean obtained for the 8,500- than for the 7,500-foot level. The data available show a steady increase in the seasonal snowfall up to 7,500 feet, with rate of increase greatest between 5,500 and 6,500 feet. Taking into consideration the distribution of the stations used for the higher levels, it seems probable that the line of heaviest snowfall is near the 9,000-foot contour line, as the average decrease between 8,500 and 9,500 feet for two groups of stations having similar exposure is only 0.5 inch. The rate of increase in seasonal snowfall with change in altitude for the State as a whole, based wholly on actual records available, is shown at the top of figure 6, while below are indicated the rates of increase for altitude along 5 profile lines crossing the Sierra Nevada and 1 crossing the mountains of southern California.

The rate of increase varies widely, being influenced by all of the factors that control the total fall of precipitation and snow. It is greatest along both slopes of the Sierra Nevada near an east to west line passing through Summit, and least in the desert region and near the coast. Due to orographic influence it may differ widely within short distances.

In studying the effect of temperature on the seasonal snowfall, only the mean temperature for the months of December, January, February, March, and April was used, as 81 percent of the total fall occurs during these months. It was found that, as a rule, cold winters were attended by more, and warm winters by less, than the normal snowfall. The average relationship is indicated in figure 7.

The mean curve is displaced to the right if the seasonal precipitation is above normal, and to the left if below normal; the total precipitation thus acts with the temperature in controlling snowfall departures. Expressed numerically, for the period from December to April, inclusive, 22 seasons were warmer and 17 colder than average. The average seasonal snowfall for the 22 warm seasons was 77 percent and for the 15 cold seasons was 129 percent of the normal. In only 8 seasons were mean temperature and snowfall departures alike; 4 warm seasons having had more and 4 cold seasons having had less than the usual amount. The mean winter and early spring temperature effect on the total precipitation was

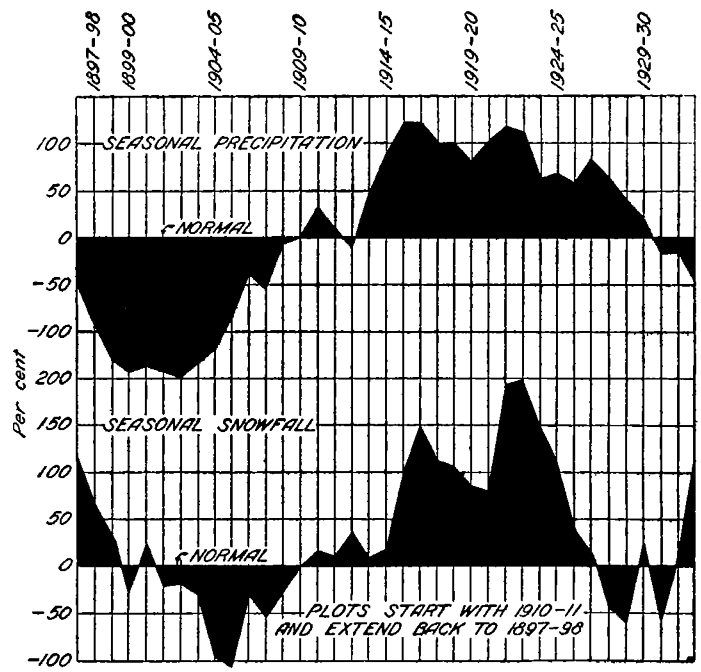

FIGURE 5.—Accumulated departures.

slight; the average for the cold was only 2 percent greater than for the warm seasons.

The percentage of the total precipitation in the form of snow is negligible below the 1,000-foot level. At 2,500 feet it ranges from 1 in southern to 10 percent in northern California; at 5,000 feet from 11 to 45 percent, depending largely on ocean influence and latitude; at 7,500 feet from 88 to 92 percent for the few stations reporting from this altitude. It is slightly less for the stations in the Owens and Mono Basins, which have an altitude of more than 9,000 feet; the lower ratio here is due to the considerable amount of precipitation that falls as rain during summer thunder storms. The percentages given are approximations because of insufficient information as to the character of precipitation and the water content of new snow.

Efforts to measure the influence of advance of season and altitude on the water content of snowfall were also inconclusive due to lack of uniform methods and refined apparatus for obtaining the water equivalent of snowfall, many observers using the commonly adopted ratio of 10 parts of snow to 1 part of water. In general, the ratio was found to be greater in mid-winter than in spring and autumn, at high than at low altitudes, and on the eastern than on the western slopes of the Sierra Nevada, temperature of the air at time of snowfall being the prime factor. Marked variations from storm to storm and season to season were indicated by otherwise unexplained differences in the water content and rate of disappearance of the snow cover.

During the average season snow begins to accumulate at the high levels late in October, and by the end of November covers the ground above the 3,500-foot level over much of the Sierra Nevada. At the close of December the snow cover has extended downward to the 2,000-foot contour line, except near the coast and in southern California, where it is somewhat higher. The snow cover has its greatest increase in depth in January, gains but little in February, due to settling and melting; then decreases in depth, with greatest loss in April. By the close of March it has receded to the 3,500-foot level in the northern portion of the State, except in areas of unusually heavy falls; and a month later it has disappeared, except in sheltered spots, up to the 5,000-foot

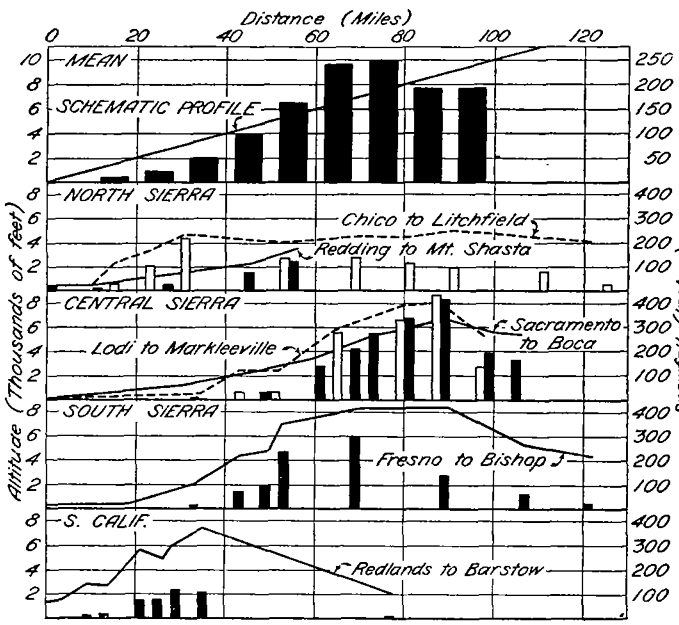

FIGURE 6.—Snowfall and altitude.

level in the more northern and up to 8,500 feet in the more southern districts. The deepest average cover for the State for the area above the 2,000-foot contour line is 13 inches near the close of January; but the greatest average depth for the high-level stations in areas of heavy snowfall occurs late in February or early in March; the heavier the average fall the later the occurrence of the greatest average depth. On March 15 the average depth of snow cover at Soda Springs is 106 inches, and at Tamarack 144 inches. The greatest depth of snow on the ground reported at any time in California was 454 inches at Tamarack on March 9, 1911. Despite such great accumulations, there is no region of entirely permanent snow cover; and the snow sometimes observed on the higher mountain peaks during July, August, and September usually is from recent storms.

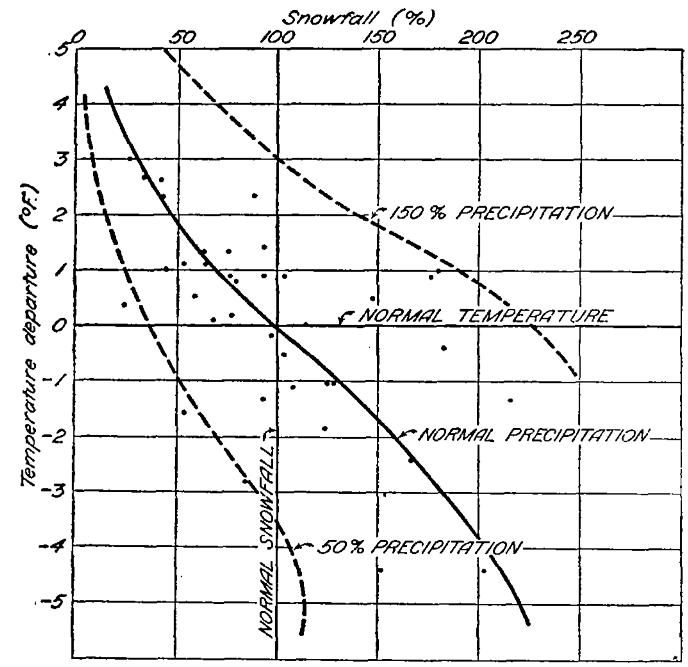

FIGURE 7.—Temperature-snowfall-precipitation relations.

The accumulated snow diminishes in area and depth by melting, settling, evaporation, and ground absorption. Rate of melting and evaporation accelerates with increase in temperature, wind movement, and amount and intensity of sunshine; settling is influenced by temperature, winter rains, and water content of the seasonal fall; and ground absorption is controlled by the condition of the soil when snow first begins to accumulate, whether frozen or unfrozen, wet or dry. It is obvious that melting is more rapid on sunny than on shaded slopes, and that deep and shaded canyons conserve the cover, unless subjected to more than average wind movement. The rate of melting varies greatly in localities where conditions seem alike, patches of snow lingering long after the first bare ground appears nearby; and it is believed that these variations are due to differences in composition, temperature, and moisture of the ground surface underlying the snow, as well as to shade and uneven distribution of the original snowfall.

The value of the seasonal snowfall as a water reserve is not measured by total fall alone, but is affected also by the monthly distribution, water equivalent, winter rainfall, and the weather factors that modify the rate and time of melting and cause alternate thawing and freezing. Water content and firmness of pack, as well as depth and area of cover, are important factors in estimating the probable spring and summer water supply. For marked contrasts in snowfall conditions, consideration need be given only to the last two seasons: The season of 1932–33 was marked by a heavy total fall, favorable monthly distribution, and cold, cloudy weather which retarded the melting of snow and ice; while the present season had a light fall, which came too early for best results, and after the first of January much warm, sunshiny weather, which caused the snow cover to disappear earlier than during seasons when the total snowfall was less.

113082—35——2